AFFORDABILITY ASSESSMENT FOR A SUBSONIC TRANSPORT

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ABSTRACT

Military budget cuts and increased competition in the commercial market have shifted the focus of aircraft design to include affordability concerns. This has resulted in the need for increased knowledge in the early stages of design when a high percentage of the available resources are committed. The Technology Identification, Evaluation and Selection methodology outlined herein provides the designer with a structured decision making method within which technological alternatives can be compared. Furthermore, this methodology is probabilistic in nature to account for the uncertainty and risk inherent in design, as well as for the variability of the aerospace market. Thus, this seven-step process leads the designer from a societal need, through a series of alternatives, to a robust solution capable of meeting customer goals within a variable environment. As a proof of concept the methodology was applied to a very large commercial transport. Evaluation criteria and potential concepts were identified through systematic techniques such as Quality Function Deployment and Morphological Matrices. The baseline concept studied could not meet all customer requirements with an acceptable degree of confidence, and therefore, three potential technologies were considered. The technologies investigated were hybrid laminar flow control, composite wing and composite fuselage, and their possible combinations. Probabilistic techniques such as Response Surface Methodology and Monte Carlo Simulation were employed to identify technically feasible and economically viable alternatives. Finally, Multi-Attribute Decision Making methods were employed to select a best alternative according to the established evaluation criteria.

INTRODUCTION

Aircraft affordability has become an increasing concern within the aerospace industry in recent years. Military budget cuts and increased competition in the commercial market have forced aircraft designers to regard cost as an additional design constraint, rather than as a secondary consideration. Thus, every decision made by a designer must be evaluated in light of the effect it will have on the life cycle cost of the aircraft, from design inception to retirement. Therefore, issues such as producibility, environmental compliance, safety, maintainability, and operational qualities must receive the same attention as performance has received in the past. However, in the early design phases, very little information regarding these considerations is available to the designer. As a result, resources are committed based on limited information and making subsequent changes can become very costly. More knowledge must be made available at the conceptual and preliminary design levels when the design freedom exists, and this design freedom must be maintained as long as possible. Such a combination of increased knowledge and extended design freedom will enable the designer to make educated decisions and commit resources wisely with the ensuing cost savings. Furthermore, the designer must account for the risk associated with making decisions based on limited information, and must recognize the inherent variability in all aspects of design, from material properties to operational environment.

The objective of this paper is to address these problems through innovative design methods that focus on bringing knowledge forward to the early design phases while accounting for uncertainty and risk. The Technology, Identification, Evaluation and Selection (TIES) methodology outlined herein is probabilistic in order to address the uncertainty surrounding the design process and associates a confidence level to all decisions made. Furthermore, this methodology allows the designer to compare multiple design alternatives according to a set of goals which include the concerns of airlines, airport officials, environmental agencies and all other parties involved. Thus, the TIES methodology can lead the designer from an intricate problem that involves conflicting goals to a robust design solution capable of accomplishing a multitude of objectives under a variety of situations. Within this paper the method is applied to a large subsonic transport aircraft to evaluate the potential costs, benefits and risks of several technology concepts and their impact on the overall aircraft affordability.

TECHNOLOGY IDENTIFICATION, EVALUATION AND SELECTION METHODOLOGY

The TIES methodology, developed at the Aerospace Systems Design Lab (ASDL), allows the designer to consider all relevant aspects of an aircraft concept, including the cost / benefit tradeoffs resulting from technology combinations. The methodology outlined here, and described in detail within Kirby et al, 1998 and Mavris et al, 1998, is implemented in seven steps:

1.- Problem Definition
2.- Identification of baseline and alternative concepts
3.- Modeling and simulation
4.- Design space exploration
5.- Determination of system feasibility and viability
6.- Population of the Pugh evaluation matrix
7.- Best alternative concept determination

The flow between these steps is depicted in Figure 1. As shown, a problem definition based on customer desires leads to the selection of a baseline and alternative concepts. These design alternatives are then evaluated within a modeling and simulation environment. This environment allows a thorough exploration of the design space in search of technically feasible and economically viable design solutions. Thus, the design concepts selected can be evaluated through multi-attribute decision-making techniques, and a best alternative can be found.

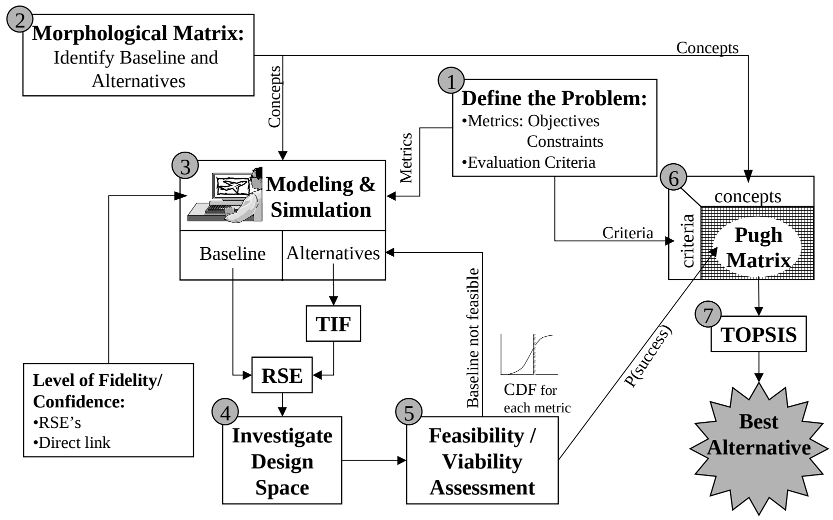

Figure 1: Technology Identification Evaluation and Selection Methodology (Mavris et al, 1998)

Step 1: Problem Definition

The first step in the TIES methodology involves identifying a societal need and addressing it through an in-depth definition of the problem. This problem definition is the foundation upon which a design solution that meets all customer goals is selected. For example, an aircraft must be affordable to develop and produce for the manufacturer. It must also meet airline expectations in terms of loading capability, range, and operating costs. It must be compatible with existing airport facilities and adhere to all applicable Federal Aviation Administration regulations. Furthermore, the aircraft must be environmentally friendly by minimizing exhaust emissions and limiting noise levels to satisfy neighborhoods in the vicinity of airports. Evidently, the problem can quickly become very complex and to make matters worse, the customer goals are often ambiguous and must be translated into quantifiable metrics. For example, an airline's desire to lower their operating costs could be translated into a lower fuel consumption or a reduced number of flight crew members. Quality Function Deployment (QFD) offers a structured means to translate the 'voice of the customer' into the 'voice of the engineer' through systematic brainstorming. For an in depth description of the QFD method the reader is referred to Kusiak, 1993.

Through the QFD process, metrics and appropriate target values to meet customer objectives can be identified. These metrics are then used to evaluate possible design concepts and to determine system technical feasibility and economic viability. However, before the system can be evaluated, it must be defined in terms of both product and process characteristics with due consideration given to its operating environment. Thus, design parameters such as wing aspect ratio or horizontal tail area must be considered alongside inherently uncertain parameters such as labor rates or cost of fuel.

Step 2: Baseline and Alternative Concepts Identification

Once the design goals and constraints are identified, a family of concepts that might meet the customer needs must be selected. However, with a system as complex as an aircraft, the possible combinations of subsystem attributes can be innumerable, and a structured way of selecting potential concepts to be evaluated is essential.

The Morphological Matrix approach, proposed by Twiss, 1992, decomposes the system into subsystem attributes, and lists the potential alternatives for each attribute. The subsystems to be addressed, such as wing material, are placed on a given row while the possible alternatives, such as aluminum, composites, etc…, are placed on corresponding columns. Then design concepts are identified by circling combinations of attributes that may contribute to meeting customer expectations. In this step, care must be taken to select combinations of attribute settings that are physically compatible with each other. For example, Hybrid Laminar Flow Control requires micro-holes that cannot currently be manufactured with composite materials.

An example of a Morphological Matrix is presented in Figure 2. In this example, four attributes (casing type, tip type, ink color and line width) are used to define a pen. For each of these attributes possible alternatives are identified. In Figure 2, the highlighted concept is a black, ball-point pen which produces a medium line width and has a metal casing. Other concepts can be selected in a similar manner.

		Alternatives		
Attributes	**Casing**	Plastic	Metal	Hybrid
	Tip	Felt	Ball	
	Ink	Black	Red	Blue
	Line Width	Fine	Medium	Heavy

Figure 2: Example Morphological Matrix (Mavris et al, 1998)

Generally an alternative containing present day technology is selected as a reference point, this is termed the baseline concept. This baseline and other potential concepts are evaluated in terms of technical feasibility and economic viability through modeling and simulation.

Step 3: Modeling and Simulation

In order to evaluate the metric values for each of the potential design concepts with a minimum program investment, a modeling and simulation environment is required. In the early stages of design the only information available is historical data. Hence, legacy codes designed to carry out tradeoffs based on this type of information are used. For unusual designs that are not included the historical database, these legacy codes can be enhanced using detailed analytical models, or their parametric representation as in Mavris et al, 1998.

Step 4: Design Space Exploration

Employing the modeling and simulation environment previously described, the values for each of the metrics of interest can be determined throughout the design space. This is accomplished through the variation of design parameters within acceptable limits as set in step 1. The resulting metric estimates are in the form of a Cumulative Density Function (CDF) which represents the confidence levels associated with each metric value. This variability is due to the uncertainty in the design, and will be particularly prominent in the economic metrics since they are also subject to the fluctuation of an operational environment.

This probabilistic analysis can be carried out through three different methods. The first and most accurate method is a Monte Carlo simulation based on the mentioned legacy codes. However, this requires a large number of code executions and may be computationally intensive. The second proposed method involves the Advanced Mean Value Fast Probability Integration technique which is described in detail in SWRI, 1995 and Mavris et al, 1997. This technique executes the analysis codes directly a limited number of times to obtain an approximate probability distribution associated with a given metric. The third possible method involves the creation of a parametric representation of the analysis code as a function of the parameters varied during the design exploration. This metamodel is then linked to a Monte Carlo simulation and again a metric probability distribution is obtained. The creation of this metamodel can be accomplished with a limited number of code executions using design of experiments techniques and response surface models as described in Mavris et al, 1995, Mavris et al, 1996 [2], and Mavris et al, 1997 [3]. In this case, the third method was chosen, however, this choice is entirely in the designers hands.

Step 5: Determination of System Feasibility and Viability

The system technical feasibility and economic viability are based on designer specified confidence levels (i.e. probability on the CDF), and the corresponding metric values. Thus, the probability distributions previously obtained must be compared to the target metric values determined in the problem definition and all customer requirements must be met with an acceptable confidence level.

Typically, the baseline solution containing readily available and proven technologies is analyzed first. If the target metric values cannot be achieved with a satisfactory degree of confidence, and these target values are non-negotiable, solutions involving enabling technologies must be investigated. However, since innovative technologies may not be fully proven and often try the limits of available analysis tools, their application carries some degree of risk. Therefore, the use of such technologies is only warranted for a specific need.

In order to model new technologies which fall outside the historical database available, the TIES methodology uses 'k-factors' to enhance or degrade disciplinary level parameters such as wing weight or fuel consumption. These k-factors account for benefits and penalties of the technologies under consideration. For example, the use of a composite wing will result in a decrease over the wing weight calculated for an aluminum structure, however, it will also result in a higher aircraft cost. Thus, for each concept identified with the aid of the Morphological Matrix, suitable penalties and benefits must be determined though expert questionnaires, physics-based modeling, and literature searches.

Modeling technologies through k-factors has the additional advantage of providing a parametric environment for the effect of each technology, which may point to the areas where technological improvement would be most beneficial. The k-factor levels for each design alternative combined with a metamodel can be used within a Monte Carlo simulation to yield metric CDF's associated with each concept.

Step 6: Population of the Pugh Evaluation Matrix

The Pugh Evaluation matrix [Pugh, 1996] provides a structured means to compare the design alternatives under consideration. This matrix contains the metrics selected for evaluation as rows, and each design concept to be considered as a column of the matrix. Once each design alternative has been analyzed, the resulting metric values are used to populate the matrix such that a value is input for each metric at each technology level.

Since the metric values obtained are in the form of probability distributions, an acceptable confidence level must be defined by the designer. The metric values associated with that confidence level are then used to populate the Pugh matrix. The selection of an admissible confidence level will be dependent on the risk and uncertainty associated with the readiness level for a particular technology.

Step 7: Best Alternative Concept Determination

The Pugh Matrix contains the metric values for each design alternative. This information is used to determine the best alternative given the target metric values previously defined. This decision can be carried out using Multi-Attribute Decision-Making (MADM) techniques such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [Hwang et al, 1981].

The TOPSIS technique utilizes the information contained in the Pugh matrix to yield a preference order for the alternatives under consideration. This decision-making technique starts by normalizing the data within each alternative by the Euclidean norm for each particular metric. Each metric is then defined as a cost or a benefit and subjectively weighted. A positive and a negative ideal solution are defined and the concepts are ranked according to the deviation from the positive ideal solution and separation from the negative ideal solution. Note that this ranking is a function of the subjective weights placed on the criteria. For more information on this technique the reader is referred to Hwang et al, 1981.

This step completes the objective of the TIES methodology. The designer is thus led from a societal need, through the comparison of several design alternatives, to the selection of a design concept that will best satisfy customer desires under a multitude of conditions.

PROOF OF CONCEPT

As a proof of concept, the TIES methodology is applied here to the design of large subsonic commercial transport similar to concepts currently under development in the aircraft industry. This type of aircraft poses a technical and economic challenge to aircraft designers and is therefore a perfect candidate for analysis through the TIES methodology.

Step 1: Problem Definition

Current forecasts, such as Airbus, 1998 [2], Boeing, 1998 and NASA, 1998 [2], expect the commercial transport market to continue growing for the next twenty years at an average rate of 5%, this means that air traffic will double in just 15 years. A portion of this traffic will be absorbed by the creation of new routes and an increase in flight frequency thanks to the deregulation of air travel in a number of countries. However, in some congested markets where the infrastructure will not be able to expand, the only solution to cope with this growth will be to use aircraft with a higher passenger capacity. Airbus Industrie [Airbus, 1998] expects that this type of large aircraft will account for 10% of the new aircraft demand in years to come, and approximately 25% of the gross business forecasted. The demand for a 600-1000 passenger transport will be especially high in the trans-pacific and intra-pacific markets. Recent economic downturns in this area are not expected to have any long term effects, and in the first years of the new millennium the demand for air travel is expected to continue growing in this region [Airbus, 1998 [2]].

However, it is not enough that the air travel need for such large aircraft is clear. Certain requirements must be met in addition to market demand to make this aircraft attractive to potential customer airlines. These requirements are presented as a comparison against the Boeing 747-400, the largest commercial transport currently available. Airlines, such as JAL and British Airways, have expressed a desire for a large subsonic transport capable of carrying between 600-1000 passengers over long and short range routes with a significant reduction (15-20%) in direct operating costs with respect to the 747 [Ramsden, 1994, Proctor, 1994 [2]]. Furthermore, airlines seek turn around times of less than 105 min which represents a 15% reduction with respect to the 747-400 [Mecham, 1994 [2]].

Airport compatibility is another major airline concern. Current gates at most airports cannot handle aircraft with wingspans greater than 80 m. Even wingspans within this constraint may require special accommodations if they do not meet turning radius requirements. Runway and taxiway separations may also present a problem with such large aircraft, as well as the runway length required to take off in fully loaded situations. These large transports can also be expected to heavily load the pavement and concrete designed to support lighter aircraft. Consequently, special landing gear designs may be necessary to distribute the load appropriately. These transports may also create a large wake turbulence, forcing a greater separation in the flight patterns and perhaps even on the ground. NASA studies are currently researching the sources of wake turbulence in order to identify solutions for this type of problems [Nordwall, 1994, NASA, 1998]. Furthermore, airport officials expect problems with the flow of such large concentrations of travelers as well as with luggage handling [Mecham, 1994, Windisch, 1994]. All of these concerns must be addressed in order to determine the feasibility of a large commercial transport.

In addition to airport concerns, these large aircraft will have to meet very stringent noise regulations and other environmental concerns dictated by the Federal Aviation Administration (FAA) such as exhaust emissions. Additional safety concerns involve evacuation of such a large number of passengers, the prevention of fire propagation within the cabin, and the large number of casualties in the event of a catastrophic failure. Airbus Industrie has applied for a Type Certificate to the FAA. This certificate is necessary before their version of a large transport, the A3xx, moves into production. Therefore they will have to address all these safety issues in their design [Airbus, 1998, Phillips, 1994, Phillips, 1994 [2]].

For aircraft manufacturers, this design presents a challenge which may be technically feasible but which may require a large investment in research and development. Such investments are risky and the aerospace industry will need a guaranteed market before programs such as this one can move to the production phase.

All these customer requirements must be translated into engineering quantitative terms using brainstorming techniques such as QFD in order to identify and evaluate potential design alternatives. In this case, airport concerns are addressed by limiting the take-off and landing field lengths to 11,000ft and the approach speed to less than 150 kts. Also in order to meet airport limitations, the wingspan will be limited to 80 m and the takeoff gross weight will be expected to be less than one million pounds. To address airline concerns, the target operating costs will be reduced 15-20% with respect to the 747-400 benchmark and the acquisition cost will be comparable to that of a 747-400 (167.5-187.0 M$ according to Boeing, 1999). To minimize the initial investment required by the aircraft manufacturer, minimum RDT&E costs will be sought. These target metric values are summarized in Table 1.

Table 1: Constraints and Targets

Metric	Constraint / Target
Take off Gross Weight	< 1,000,000 lbs
Take off Field Length	< 11,000 ft
Landing Field Length	< 11,000 ft
Approach Speed	< 150 kts
Acquisition Price	~ 190 M$
RDT&E Costs	Minimize
Direct Operating Costs per Available Seat Mile	~ 2.450 ¢/ASM
Required Average Yield per Revenue Passenger Mile	~ 0.095 $/RPM

These constraints will have to be achieved within an acceptable design space while accounting for the uncertainty of a changing market. In this case a conventional large transport design will be considered with a capacity of 600 passengers and a design range of 7500 nmi [Barlett et al, 1992, Sparaco, 1994]. Additional design parameters and their admissible ranges are presented in Table 2. Economic assumptions and economic parameter intervals considered likely are shown in Table 3 and in Table 4 [Mavris et al, 1996, Mavris et al, 1997 [2]]. Note that the lower limit for the load factor (percent of seats occupied) is below 50%, this is to account for certain routes that may not have the necessary passenger traffic to utilize all the available seating.

Table 2: Design Variable Ranges

	Minimum	Maximum
Mach Number	0.78	0.83
Horizontal Tail Area (ft^2)	1225	1400
Thrust to Weight Ratio	0.24	0.28
Vertical Tail Area (ft^2)	900	1400
Wing Aspect Ratio	8	10.5
Wing Area (ft^2)	5800	6800
Wing Sweep (deg.)	22	40
Thickness to Chord Ratio	0.09	0.11

Table 3: Economic assumptions

Assumptions	
Maintenance Labor Rate	25 $/hr
Maintenance Burden	200%
Hull Insurance	35%
Depreciation Period	20 yrs
Residual Salvage Value	10%
Airframe Spares	6%
Engine Spares	23%
Interest Rate	8%
Year Dollars	1996
Production Period	15 yrs

Table 4: Market Variability Definition

	Minimum	Maximum	Most Likely
Airline Return on Investment	5%	15%	7%
Manufacturer Return on Investment	10%	20%	15%
Economic Range (nmi)	3000	7000	3500
Fuel Cost per Gallon	0.40	0.90	0.70
Manufacturing Learning Curve	74	82	78
Production Quantity	650	1150	800
Utilization (hrs/yr)	4500	5500	5000
Load Factor	0.45	0.85	0.65

Step 2: Baseline and Alternative Concepts Identification

As described previously, a Morphological Matrix can be used to identify a baseline concept and potential technology alternatives to address the customer needs. In this case, three subsystems were considered beyond the baseline settings that allowed for high aspect ratios. The three subsystem attributes considered were wing material, fuselage material and Hybrid Laminar Flow Control (HLFC) [Arcara et al, 1993, Barlett et al, 1992]. The morphological matrix used in this implementation of the TIES methodology is shown in Figure 3 reflecting the baseline concept. This matrix resulted in the alternatives shown in Table 5. Note that some of these alternatives are not feasible with today's technology, but they were included in the analysis for the sake of completeness.

		Settings	
Attributes	**Wing Material**	Aluminum	Composite
	Fuselage Material	Aluminum	Composite
	Hybrid Laminar Flow Control	Yes	No

Figure 3: Morphological Matrix for a Large Subsonic Transport

Table 5: Design Alternatives for a Large Subsonic Transport

		Baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
Attributes	**Wing Material**	Aluminum	Composite	Aluminum	Aluminum	Composite	Composite	Composite	Aluminum
	Fuselage Material	Aluminum	Aluminum	Aluminum	Composite	Aluminum	Composite	Composite	Composite
	Hybrid Laminar Flow Control	No	No	Yes	No	Yes	No	Yes	Yes
	Possible Combination with Today's Technology	Y	Y	Y	Y	N	Y	N	Y

Step 3: Modeling and Simulation

The metrics of interest were estimated for each alternative under scrutiny within the modeling and simulation environment depicted in Figure 4. This environment was formed by a public domain synthesis and sizing tool termed FLOPS [McCullers, 1998] and an economic analysis tool originally developed by NASA [Galloway et al, 1993], and enhanced at the Aerospace Systems Design Laboratory designated as ALCCA [Garcia et al, 1999]. Design of Experiments, Response Surface Methods and Monte Carlo simulation techniques were employed to obtain probability distributions for each metric.

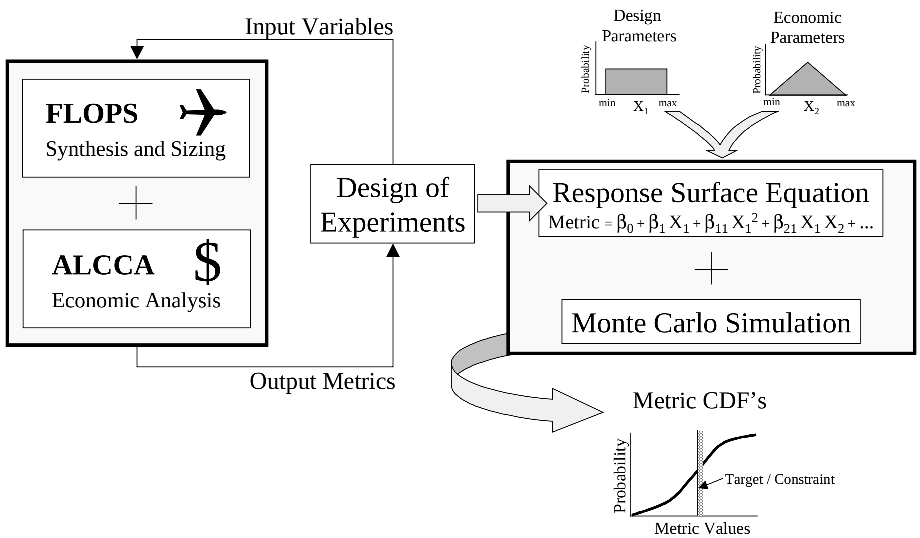

Figure 4: Modeling and Simulation Environment

Step 4: Design Space Exploration

The design alternatives under consideration must be analyzed throughout the design space within the modeling and simulation environment described. The baseline concept was evaluated first since it represents present day technology. In order to carry out this analysis in a probabilistic manner, a metamodel describing the metrics of interest as a function of the design and economic parameters under consideration was created. This metamodel was assembled through a fractional factorial design of experiments for 16 variables [Montgomery, 1991] and a response surface fit [Box et al, 1987] using a commercial computer package for statistical analysis named JMP [SAS Institute, 1994]. See Figure 5 for a graphical representation of the metrics as a function of the variables considered, this type of representation is termed Prediction Profile.

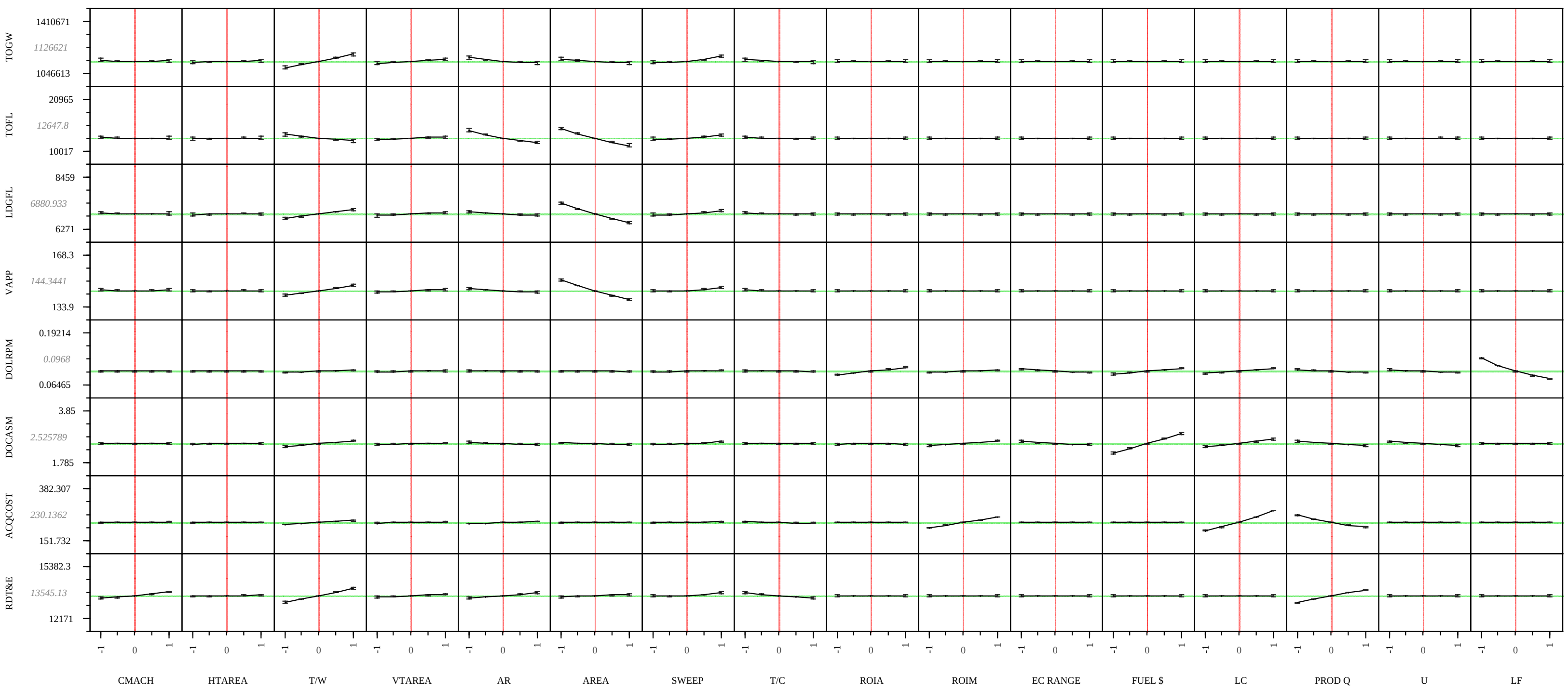

Figure 5: Prediction Profiles

Once a metamodel was constructed using the variable ranges defined in Table 2 and in Table 4, a Monte Carlo simulation was run with the aid of Crystal Ball a commercially available software [Decisioneering, 1993]. In running this Monte Carlo simulation, design variables were given a uniform probability distribution in order to investigate the entire design space. Economic variables were given triangular distributions with the apex set at their most likely values as listed in Table 4. This Monte Carlo simulation yield cumulative distribution functions (CDF) for each of the metrics considered.

Step 5: Determination of System Feasibility and Viability

The first step in determining system technical feasibility and economic viability was to define an acceptable confidence level. In this case, a 75% confidence of meeting the metric target values described in Table 1 was desired. The confidence level achieved was determined using the CDF's generated in the previous steps and finding the cumulative probability of achieving a certain metric value. For example, Figure 6 shows that the baseline concept only had a 5% chance of meeting the 11,000 ft take-off field length design constraint. Table 6 summarizes the probability of meeting the predefined goals for the baseline concept under the stated assumptions.

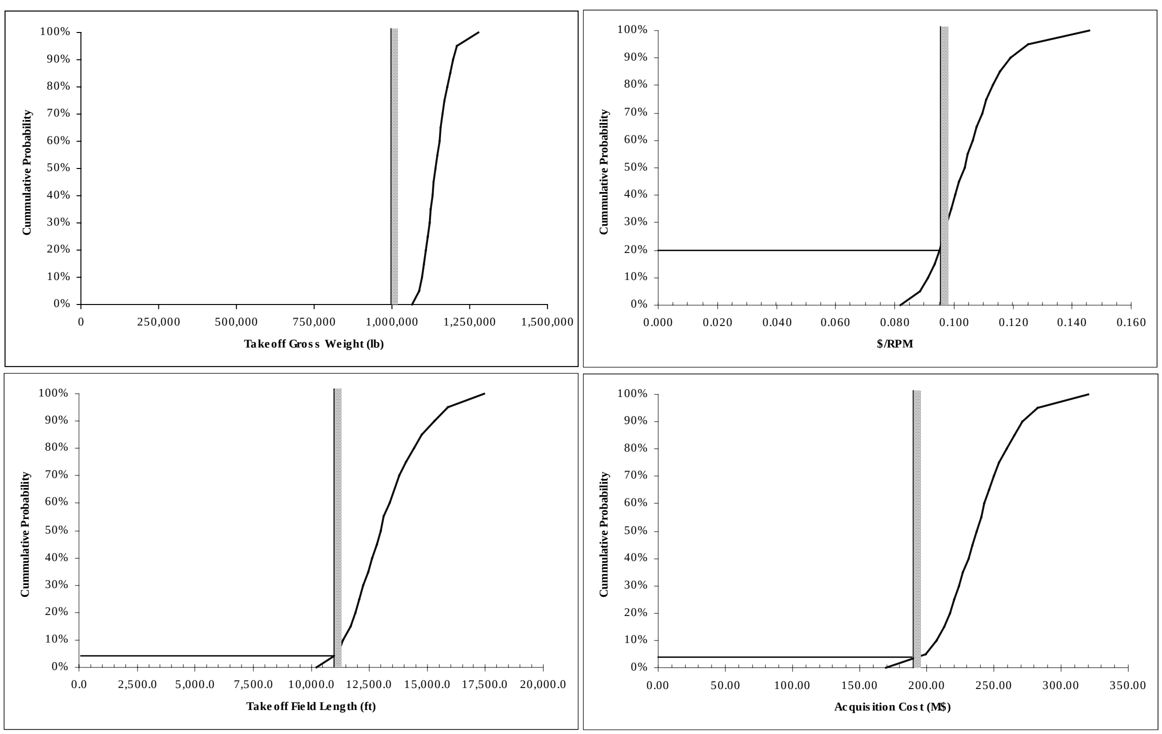

Figure 6: Sample Cumulative Distribution Function

Table 6: Summary Results for Baseline concept

Criteria	Probability of Achieving Target Value
Take off Gross Weight	0%
Take off Field Length	5%
Landing Field Length	100%
Approach Speed	85%
$ / RPM	25%
Acquisition Cost	5%
DOC/ ASM	20%

Given the low confidence with which the baseline concept met the established constraints (with the exception of the landing field length and the approach speed), other design alternatives had to be considered. In order to assess the effect of added technologies, k-factors were used to model the penalties and benefits associated with each design alternative. The k-factors considered along with their ranges are shown in Table 7.

Table 7: Ranges for Technology K-factors

K-Factor	Maximum	Minimum
k-Drag	-10%	+5%
k-Wing Weight	-20%	+5%
k-Fuselage Weight	-25%	+5%
k- Fuel Flow	-5%	+5%
k-Utilization	-5%	+5%
k-RDT&E	-5%	+5%
k-First Unit Cost	-5%	+5%
k- Operations and Support	-5%	+5%

In order to assess the effect of the technology factors alone, the economic variables were set at their most likely values and 'optimal' settings were obtained for the design variables. This 'best' design was determined using the desirability function built into JMP and described in some detail within Derringer et al, 1980. This function allows for the optimization of a multi-attribute, multi-objective problem in a graphical manner. The desirability functions are set for each of the metrics to be optimized, yielding interactive plots that represent the system desirability as a function of each of the variables under consideration. As the value of a certain variable is changed, the desirability function is updated, and the optimal solution (maximum value of the desirability function) within the defined design space can be found.

Performing an analysis similar to that in step four, design of experiments and response surface equations were combined to yield a metamodel of each criteria as a function of the k-factors varied. This metamodel combined with the k-factor levels and their estimated variability shown in Table 8 was then used to run a Monte Carlo simulation and determine the value of each metric with an associated confidence level for each technology level. Note that the k-factor values chosen for each technology level account for both benefits and penalties of each technology [Kirby et al, 1998, Mavris et al, 1998, Barlett et al, 1992.]

Table 8: K-factor Values for each Technology Alternative

	k-Drag	k-Wing Wt.	k-Fuselage Wt.	k-Fuel Flow	k-Utilization	k-RDT&E	k-T1	k-OandS
Baseline	+0%	+0%	+0%	+0%	+0%	+0%	+0%	+0%
Alt. 1	+0%	-20%	+0%	+0%	-2%	+3%	+3%	+2%
Alt. 2	-10%	+2%	+0%	+1%	-2%	+3%	+3%	+2%
Alt. 3	+0%	+0%	-25%	+0%	-2%	+3%	+3%	+2%
Alt. 4	-10%	-18%	+0%	+1%	-4%	+6%	+6%	+4%
Alt. 5	+0%	-20%	-25%	+0%	-4%	+6%	+6%	+4%
Alt. 6	-10%	-18%	-25%	+1%	-6%	+9%	+9%	+6%
Alt. 7	-10%	+0%	-25%	+1%	-4%	+6%	+6%	+4%
Estimated Variability	0.010	0.010	0.010	0.010	3.000	0.005	0.005	0.005

Step 6: Population of the Pugh Matrix

Once cumulative density functions were obtained for each metric at each technology level considered, these probability distributions can be used to estimate the metric values obtainable with a given degree of confidence. The metric values obtainable with a 75% confidence for each design alternative under consideration are displayed in Figure 7. These values will be used in step seven of the TIES methodology to determine which design concept best conforms to the requirements imposed. Note that target values which are not met at this confidence level are italicized.

Conf. = 75%	Baseline	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7
TOGW (lb)	*1,102,236*	991,292	*1,019,183*	*1,032,531*	923,271	929,524	866,698	945,611
TOFL (ft)	*11,384*	10,040	10,373	10,531	9,261	9,333	8,653	9,514
LDGFL (ft)	6,471	6,072	6,172	6,220	5,826	5,849	5,622	5,907
VAPP (kts)	137.38	130.32	132.10	132.96	125.80	126.23	121.94	127.31
DOLRPM ($/RPM)	0.09141	0.08926	0.09120	0.09103	0.08946	0.08897	0.08931	0.09045
DOCASM (¢/ASM)	2.433	2.289	2.351	2.373	2.228	2.232	2.177	2.274
ACQ (M$)	*240.77*	*225.93*	*240.64*	*232.93*	*226.93*	*218.05*	*218.66*	*230.52*
RDT&E (M$)	13,226	12,702	13,327	13,065	12,846	12,527	12,668	13,065

Figure 7: Pugh Evaluation Matrix for a Large Subsonic Transport

Step 7: Best Alternative Concept Determination

The information displayed in the Pugh matrix is used in combination with the TOPSIS technique described previously in order to rank the design alternatives under consideration from best to worse. Since the rankings depends on the weighting selected for the metrics, and this weighting is purely subjective, the TOPSIS method is repeated for several weighting combinations ranging from an emphasis in pure performance, to a heavy stress on the econometrics. The rankings determined by TOPSIS, along with the weighting factors that generated them are presented in Figure 1. Note that the weighting factors must add up to one.

	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank
TOGW lb	0.125	6	0.250	6	0.050	6	0.000	5	0.120	6
TOFL ft	0.125	5	0.250	4	0.050	5	0.000	6	0.120	5
LDGFL ft	0.125	4	0.250	5	0.050	4	0.000	1	0.020	4
Vapp kts	0.125	7	0.250	7	0.050	1	0.000	4	0.020	7
$/RPM	0.125	1	0.000	1	0.200	7	0.250	7	0.340	1
Acq M$	0.125	2	0.000	2	0.200	3	0.250	3	0.340	3
RDT&E M$	0.125	3	0.000	3	0.200	2	0.250	2	0.020	2
DOC / ASM	0.125	Baseline	0.000	Baseline	0.200	Baseline	0.250	Baseline	0.020	Baseline

Figure 8: TOPSIS Results for a Large Transport

The results in Figure 8 show that alternatives 4, 5 and 6 were the best for a variety of weighting factor combinations. However, alternatives 4 and 6 involve Hybrid Laminar Flow Control combined with a composite wing. The manufacturing technology currently available does not allow for this type of combinations, therefore, alternative 5, which involves composite structures for the wing and the fuselage, was chosen as the best possible alternative.

Once a best alternative is chosen, in this case alternative 5, steps 3 through 5 of the TIES methodology must be repeated to determine the feasibility and viability of the selected alternative. As an example, Figure 9 shows that, in spite of the economic penalties imposed on this alternative, the composite weight reduction results in an overall decrease in operating costs for the aircraft.

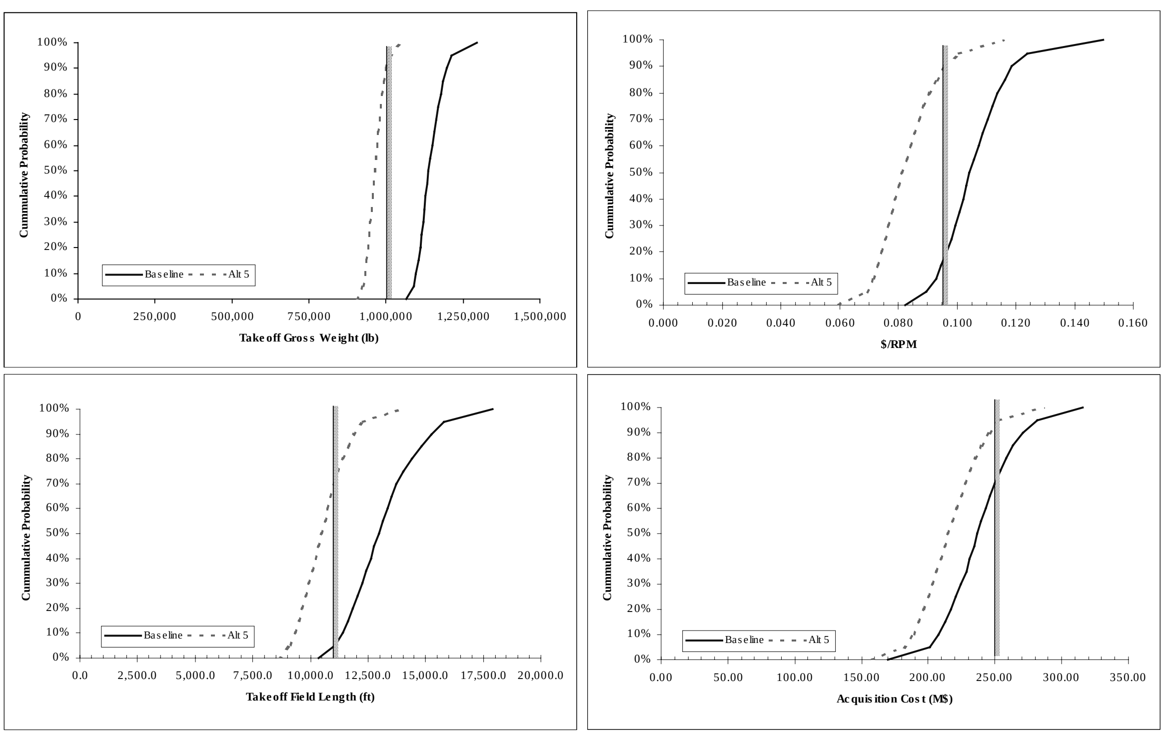

Figure 9: Comparison of Baseline and Alternative 5

Table 9: Metric Values Achieved with 75% Confidence for Alternative 5

	Alternative 5	Target
Takeoff Gross Weight	929,524	< 1,000,000 lbs
Takeoff Field Length	9,333	< 11,000 ft
Landing Field Length	5,849	< 11,000 ft
Approach Speed	126.23	< 150 kts
$/ RPM	0.089	~ 0.095 $/ASM
DOC / ASM	2.232	~ 2.450 ¢/ASM
Acq. Cost	*218.05*	~ 190 M$
RDT&E	12,527	Minimize

According to Table 9 all target metric values are met with at least a 75% confidence level except for the acquisition cost which is still slightly larger than that advertised by the Boeing company for the 747-400. However, the productivity (payload · rage) of this aircraft is almost a hundred percent higher than that of the Boeing 747-400. Therefore, the increased acquisition cost is justifiable in terms of the enhanced potential profit.

CONCLUSIONS

The Technology Identification, Evaluation and Selection methodology presented here has been demonstrated for a very large commercial subsonic transport, leading the designer from a problem definition, through a series of alternatives, to a final concept that meets all the established feasibility and affordability criteria. The identification of a ‘best’ concept allows proper allocation of resources with the subsequent economic benefits. Note that this methodology accounts for the inherent variability of a complex system as well as for the uncertainty and risk of a varying market. This enables the designer to make decisions which will lead to robust systems capable of accomplishing their goals within a highly uncertain environment.

This study has also demonstrated the potential opening of the design space with the infusion of new technologies. For further study, additional technologies should be considered. Due to the high impact of fuel consumption on direct operating costs technologies regarding improved fuel efficiency might be of particular interest.

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BIOGRAPHICAL SKETCH

Elena Garcia

Ms. Garcia was born and raised in Madrid, Spain. In 1992 she came to the United States to study Aerospace Engineering seeking an environment more oriented to practical application than that existing in the Spanish university system. She graduated in 1996 from the University of Virginia with a B.S. in Aerospace Engineering. In the fall of 1996 she entered the aerospace engineering graduate program at the Georgia Institute of Technology and joined the Aerospace Systems Design Lab. In December of 1997 she received an M.S. degree in Aerospace Engineering and joined the Ph.D. program under the supervision of Dr. Dimitri Mavris. Her graduate research is focused in the cost estimation area as it relates to aircraft affordability. It only constitutes a portion of the research under way at ASDL regarding conceptual design methods.

Dr. Dimitri Mavris

Dr. Dimitri N. Mavris received a Bachelor's of Science degree in Aerospace Engineering with highest honors from the Georgia Institute of Technology in September 1984. He subsequently entered the graduate program at Georgia Tech and was awarded a CERWAT (Center of Excellence in Rotary Wing Technology) Fellowship. In 1985 he won the first prize in the annual AHS (American Helicopter Society) - Boeing Vertol student helicopter design competition. He earned his Master's of Science degree in December of 1985, and his Doctor of Philosophy degree in December of 1988. His thesis dissertation title was "An Analytical Method for the Prediction of Unsteady Rotor/Airframe Interactions in Forward Flight".

Dr. Mavris remained at Georgia Tech as a Post Doctoral Fellow, conducting sponsored research in the area of rotorcraft/aircraft design. Since 1992, he has served as the associate director and manager of the Aerospace Systems Design Laboratory and in that role is responsible for the research of 30 graduate students working in a variety of sponsored research funded by the U.S. Army, Air Force, Navy, NASA, and various aircraft and engine manufacturers. His academic career started in June of 1995 when he was offered a visiting assistant professor position at Georgia Tech. After promotion in 1996, Dr. Mavris is presently an assistant professor on a tenure track at the School of Aerospace Engineering.